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Laser Induced Shock Waves and Vaporization in Biological Systems and Material Science

Bernard S. Gerstman
Department of Physics
Florida International University
Miami, FL 33199

Abstract

Theoretical and computational work was carried out to investigate the underlying physical mechanisms that cause laser induced biological damage and material stress. In order to cause damage to the absorbing material, the electromagnetic energy of the laser pulse must be converted to thermo-mechanical energy. We have developed a computational model that allows the calculation of damage resulting from a laser pulse of any duration or energy due to temperature rise, explosive bubble formation, and shock wave production. We have discovered that the system exhibits chaotic dynamics. We have shown quantitatively that the chaos inherent in the system leads to the surprising result that small changes in laser parameters, such as duration or energy, can produce large changes in the thermo-mechanical response of the system. This causes certain laser pulse durations and energies to be especially difficult to protect against, whereas other laser regimes are especially safe. We also discovered resonant effects in laser absorption and damage that allow the duration between pulses to be tuned to channel a greater or lesser fraction of the absorbed energy into shockfront and bubble production. This allows the delivery of large amounts of laser energy to produce strong thermal effects while suppressing unwanted pressure effects, or vice versa.

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11200 SW 8th St
Miami, FL 33199

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14. ABSTRACT

Theoretical and computational work was carried out to investigate the underlying physical mechanisms that cause laser induced biological damage and material stress. In order to cause damage to the absorbing material, the electromagnetic energy of the laser pulse must be converted to thermo-mechanical energy. We have developed a computational model that allows the calculation of damage resulting from a laser pulse of any duration or energy due to temperature rise, explosive bubble formation, and shock wave production. We have discovered that the system exhibits chaotic dynamics. We have shown quantitatively that the chaos inherent in the system leads to the surprising result that small changes in laser parameters, such as duration or energy, can produce large changes in the thermo-mechanical response of the system. This causes certain laser pulse durations and energies to be especially difficult to protect against, whereas other laser regimes are especially safe. We also discovered resonant effects in laser absorption and damage that allow the duration between pulses to be tuned to channel a greater or lesser fraction of the absorbed energy into

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The following summaries are of results that were discovered by the research funded by this grant. These results are documented in detail in readily accessible published papers, which are referenced on a separate page.

1) Damage by pulsed lasers to the retina or other tissues containing strongly absorbing particles may occur through biophysical mechanisms other than simple heating. Shockwaves and bubbles have been observed experimentally, and depending on pulse duration, may be the cause of retinal damage at threshold fluence levels. We performed detailed calculations on the shockwave and bubble generation expected from pulsed lasers. For a variety of different laser pulse durations and fluences, we tabulated the expected strength of the shockwave and size of the bubble that will be generated. We also explain how these results will change for absorbing particles with different physical properties such as absorption coefficient, bulk modulus, or thermal expansion coefficient. This enables the assessment of biological danger, and possible medical benefits, for lasers of a wide range of pulse durations and energies, incident on tissues with absorbing particles with a variety of thermomechanical characteristics.

2) We discovered that the simple system of a spherical absorber immersed in water can exhibit complex and chaotic behavior upon absorption of laser energy. We developed a method to perform computer experiments on this simple system to quantify the chaotic response. We presented power spectra and calculated Lyapunov exponents that show that for increasing laser pulse durations and increasing laser energy the pressure response of the system changes from periodic to a regime displaying spatiotemporal chaos. This is important from a theoretical point of view because the complex behavior displayed in this simple system makes it an excellent choice for investigations into the nonlinear dynamics of fluids and the complicated transition to turbulence. This is also important for people using these systems for various applications in material science and biomedicine.

3) We investigated the thermomechanical response of a spherical absorber to multiple pulses of laser radiation and the potential for causing damage to the absorber and the surrounding material due to shockwave and bubble formation. We calculate the expected response of a spherical absorber to a series of laser pulses as a function of the gap duration between the pulses. We modeled two common absorbers that have different characteristics: a 1 μm melanosome found in the retina, and a 100 nm gold particle. We find that the thermomechanical response strongly depends on the duration between pulses and displays resonant effects with a characteristic period that depends on the absorber properties. This allows tuning the duration between pulses to channel a greater or lesser fraction of the absorbed energy into shockfront and bubble production, presenting various possibilities such as delivering large amounts of laser energy to produce strong thermal effects while suppressing unwanted pressure effects in the surrounding material. Resonance can also be used to target absorbers of a specific size, allowing generation of shockfronts in localized target regions to destroy specific cells. This specificity can also be used to sort particles by size.

4) Laser generation of high pressures and bubbles can cause severe effects in biological tissue and it is important to know the potential for damage prior to laser application. We

investigated the dependence of the thermomechanical response of an absorber on the temporal profile of the intensity of a laser pulse. We found that pulse duration and energy are not sufficient to predict the potential for damage. There are important situations where the pressure and bubble generation depend strongly on the pulse's temporal profile. We defined an effective pulse duration, τ_L, and explained its importance in determining pressure and bubble generation. We showed how the correct combinations of pulse duration and pulse shape allow unwanted thermomechanical effects to be minimized. Our work is relevant to researchers wishing to compare and contrast results obtained from simplified tophat temporal pulse profile models with studies of real laser profiles.

REFERENCES

Journals

E. Faraggi, B.S. Gerstman, and J.M. Sun
"Biophysical Effects of Pulsed Lasers in the Retina and Other Biological Tissues With Strongly Absorbing Particles: Shockwave and Explosive Bubble Generation"
The Journal of Biomedical Optics, **10(6)**, 064029, 2005.

B. S. Gerstman
"Investigating The Nanoparticle Transition From Bulk Behavior to Discrete Atom/Finite Size Behavior Using Laser Induced Pressure Generation"
Solid State Phenomena**, 122**, 1025-1028, 2007.

E. Faraggi, B. S. Gerstman, and J. Sun
"The Emergence of Chaos in a Laser Irradiated Spherical Absorber"
Chaos, **17**, 013101, 2007

E. Faraggi and B. S. Gerstman
"Resonant Absorption of Pulsed Laser Radiation by a Spherical Absorber"
Journal of Applied Physics, **102**, 123505, 1-15, 2007

S. Wang, E. Faraggi, and B. S. Gerstman
"Pressure waves and bubble growth produced by spherical absorbers in response to laser pulses of various intensity temporal profiles"
In preparation.

Conference Proceedings

B.S. Gerstman, S. Wang, and E. Faraggi,
"Ab-Initio Calculations for Shock Wave and Bubble Production with Gaussian Temporal Laser Pulses"
Proceedings of SPIE, vol. **5319**, July 2004, p. 217-223.

Eshel Faraggi, Bernard S. Gerstman, and Shijun Wang,
"Response to Pulsed Radiation by a Spherical Solid Absorber Immersed in a Transparent Fluid"
Proceedings of SPIE, vol. **5696**, March 2005, p. 101-109.

Eshel Faraggi , Shijun Wang and Bernard Gerstman,
"Stress Confinement, Shock Wave Formation and Laser Induced Damage"
Proceedings of SPIE, vol. **5695**, April 2005, p. 209-215.

Eshel Faraggi and Bernard S. Gerstman,
"Resonant absorption in nanometer gold spherical particles"
Proceedings of SPIE, vol. **6084,** March, 2006.

Bernard S. Gerstman, Eshel Faraggi, Jinming Sun,
"Chaos in the Pressure Generated by Laser Absorption by Microparticles"
Proceedings of SPIE, vol. **6084**, March, 2006.

Bernard S. Gerstman and Eshel Faraggi,
"Analyzing chaos in the pressure generated by laser absorption by microparticles"
Proceedings of SPIE, vol. **6436**, 643617, February, 2007.

Book Chapters

Using Laser Induced Shock Waves to Investigate Nanoparticle Thermomechanical Properties,
Shock Compression of Condensed Matter – 2007, p. 703-706,
Editor(s): M. Elert, M. D. Furnish, R. Chau, N. Holmes, J. Nguyen,
Proceedings of the 15th APS Topical Conference on Shock Compression of Condensed Matter, AIP Conference Proceedings 955, Melville, New York, 2007.
ISBN 978-0-7354-0469-4.

Ph.D. Dissertations

"The Non-Linear Acousto-Mechanical and Thermodynamic Response of Spherical Absorbers to Laser Pulses of Various Temporal Profiles"
Shijun Wang
Department of Physics
Florida International University
2005